

Introduction to Quantum Metrology

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Quantum Standards and Instrumentation

 Springer

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Preface

Quantum metrology is a field of theoretical and experimental study of high-resolution and high-accuracy methods for measurement of physical quantities based on quantum mechanics, particularly using quantum entanglement. Without equivalent in classical mechanics, quantum entanglement of particles or other quantum systems is an unusual phenomenon in which the state of a system can be determined better than the state of its parts. Attempts are made to use new measurement strategies and physical systems in order to attain measurement accuracy never achieved so far.

Quantum metrology sprang into existence at the beginning of the twentieth century, along with quantum mechanics. After all, the Heisenberg uncertainty principle, together with the Schrödinger equation and the Pauli exclusion principle constituting the basis of the formalism of quantum mechanics, is also the fundamental equation of quantum metrology. The uncertainty principle sets limits to measurement accuracy, but has no relation to the technical realization of the measurement.

Quantum metrology only started to develop in the latter half of the twentieth century, following the discovery of phenomena of fundamental importance to this field, such as the Josephson effect, the quantum Hall effect or the tunneling of elementary particles (electrons, Cooper pairs) through a potential barrier. Using new important physical advances, quantum metrology also contributes to progress in physics. In the past 50 years the Nobel Prize was awarded for 16 achievements strongly related to quantum metrology. In 1964 Townes, Basov and Prokhorov received the Nobel Prize *for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle*. Presently masers constitute a group of atomic clocks, installed in metrology laboratories as well as on satellites of GPS and GLONASS navigation systems. Gas lasers are basic instruments in interferometers used in metrology of length, and semiconductor lasers are used in industrial measurements. Haroche and Wineland were awarded the Nobel Prize in 2012 *for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems*, that is, for studies in the field of quantum metrology. In 1964–2012 the Nobel Prize was awarded for important discoveries such as *the Josephson effect* (Josephson

1973), *the quantum Hall effect* (von Klitzing 1985), and *the scanning tunneling microscope* (Röhrer and Binnig 1986). Thus, scientific achievements in quantum metrology or relevant to this field are considered very important for science in general.

Currently, the major field of practical application of quantum metrology is the development of standards of measurement units based on quantum effects. Quantum standards are globally available universal primary standards that allow to realize a given unit at any place on the Earth by measurements which, in appropriate conditions, will yield equal results anywhere. The creation of quantum standards of the base units of the International System (SI) is in accordance with the objectives set by the International Committee for Weights and Measures and realized in collaboration with the International Bureau of Weights and Measures (BIPM).

This book provides a description of selected phenomena, standards, and quantum devices most widely used in metrology laboratories, in scientific research, and in practice.

The book opens with a discussion of the theoretical grounds of quantum metrology, including the limitations of the measurement accuracy implied by theoretical physics, namely the Heisenberg uncertainty principle and the existence of energy resolution limits, discussed in Chap. 1. Providing the rudiments of systems of measurements, Chap. 2 discusses the currently adopted standards for the realization of SI units, and the changes in the classical system of units allowed by quantum metrology. Chapter 3 is devoted to the activities and proposals aimed at the development of a new system of units to replace the SI system, with units of measurement defined in relation to fundamental physical and atomic constants. Chapters 4, 6, 9, 10, and 12 present the theory and practical realizations of quantum standards of units of various quantities: the voltage standard using the Josephson effect, the resistance standard based on the quantum Hall effect, the atomic clock-based frequency standard, the length standard using laser interferometry, and the mass standard based on the masses of atoms and particles. Chapter 11 is devoted to scanning probe microscopy. Chapters 5 and 8 discuss sensitive electronic components and sensors based on quantum effects and including, among others, superconducting quantum interference magnetometers (SQUIDs), single electron tunneling transistors (SETT), and advanced quantum voltage-to-frequency converters based on the Josephson junction. Presented in Chap. 5 along with many application systems, SQUIDs are *the most sensitive of all sensors of all physical quantities*.

The description of the discussed devices and the underlying physical effects is complemented by a presentation of standardization methods and principles of comparison between quantum standards (with the time standard used as an example) in accordance with the hierarchy of the system of units.

Intended to serve as a textbook, this book also represents an up-to-date and hopefully inspiring monograph, which contributes to scientific progress. As a scientific survey it puts in order the fundamental problems related to electrical metrology, the universal standards, and the standardization methods recommended

by BIPM. As an academic textbook it propagates a new approach to metrology, with more emphasis laid on its connection with physics, which is of much importance for the constantly developing technologies, particularly nanotechnology.

Large parts of this publication represent a translation from my book *Introduction to Quantum Metrology* published in Polish by Publishing House of Poznan University of Technology in 2007 and used here in translation with the publisher's permission.

I thank all those who helped me collect material for this book. Special thanks go to my colleagues at the Polish Central Office of Measures in Warsaw and at Physikalisch-Technische Bundesanstalt in Braunschweig.

Poznan, Poland

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Contents

1	Theoretical Background of Quantum Metrology	1
1.1	Introduction	1
1.2	Schrödinger Equation and Pauli Exclusion Principle	3
1.3	Heisenberg Uncertainty Principle	6
1.4	Limits of Measurement Resolution	8
	References.	10
2	Measures, Standards and Systems of Units	11
2.1	History of Systems of Measurement	11
2.2	The International System of Units (SI).	14
2.3	Measurements and Standards of Length.	18
2.4	Measurements and Standards of Mass	22
2.5	Clocks and Measurements of Time	25
2.6	Temperature Scales	30
2.7	Standards of Electrical Quantities	35
	References.	39
3	The New SI System of Units—The Quantum SI	41
3.1	Towards the New System of Units	41
3.2	Units of Measure Based on Fundamental Physical Constants	44
3.3	New Definitions of the Kilogram	46
3.4	New Definitions of the Ampere, Kelvin and Mole	48
3.5	Quantum Metrological Triangle and Pyramid	51
	References.	56
4	Quantum Voltage Standards	59
4.1	Superconductivity	59
4.1.1	Superconducting Materials	59
4.1.2	Theories of Superconductivity	63
4.1.3	Properties of Superconductors.	64

4.2	Josephson Effect	65
4.3	Josephson Junctions	69
4.4	Voltage Standards	73
4.4.1	Voltage Standards with Weston Cells	73
4.4.2	DC Voltage Josephson Standards	75
4.4.3	AC Voltage Josephson Standards	77
4.4.4	Voltage Standard at GUM	80
4.4.5	Comparison GUM Standard with the BIPM Standard	83
4.4.6	Precision Comparator Circuits	84
4.5	Superconductor Digital Circuits	85
4.5.1	Prospective Development of Semiconductor Digital Circuits	85
4.5.2	Digital Circuits with Josephson Junctions.	86
4.6	Other Applications of Josephson Junctions.	89
4.6.1	Voltage-to-Frequency Converter	89
4.6.2	Source of Terahertz Radiation	91
	References.	91
5	SQUID Detectors of Magnetic Flux	93
5.1	Quantization of Magnetic Flux	93
5.2	RF-SQUID.	98
5.2.1	RF-SQUID Equation	98
5.2.2	Measurement System with an RF-SQUID	99
5.3	DC-SQUID	101
5.3.1	DC-SQUID Equation.	101
5.3.2	Energy Resolution and Noise of the DC-SQUID.	107
5.3.3	Parameters of a DC-SQUID	110
5.4	Measurement System with a DC-SQUID	111
5.4.1	Operation of the Measurement System.	111
5.4.2	Input Circuit.	113
5.4.3	Two-SQUID Measurement System	116
5.4.4	SQUID Measurement System with Additional Positive Feedback	117
5.4.5	Digital SQUID Measurement System.	119
5.5	Magnetic Measurements with SQUID Systems	120
5.5.1	Magnetic Signals and Interference.	120
5.5.2	Biomagnetic Studies	122
5.5.3	Nondestructive Evaluation of Materials	125
5.6	SQUID Noise Thermometers	127
5.6.1	R-SQUID Noise Thermometer	127
5.6.2	DC-SQUID Noise Thermometer	130
5.6.3	Other Applications of SQUIDS	132
	References.	133

6	Quantum Hall Effect and the Resistance Standard	135
6.1	Hall Effect	135
6.2	Quantum Hall Effect	137
6.2.1	Electronic Devices with 2-DEG	137
6.2.2	Physical Grounds of the Quantum Hall Effect	138
6.2.3	QHE Samples.	141
6.2.4	Quantum Hall Effect in Graphene	144
6.3	Measurement Setup of the Classical Electrical Resistance Standard at the GUM	145
6.4	Quantum Standard Measurement Systems	149
6.5	Quantum Standard of Electrical Resistance in the SI System	152
	References.	154
7	Quantization of Electrical and Thermal Conductance in Nanostructures	157
7.1	Theories of Electrical Conduction	157
7.2	Macroscopic and Nanoscale Structures	162
7.3	Studies of Conductance Quantization in Nanostructures	163
7.3.1	Formation of Nanostructures	163
7.3.2	Measurements of Dynamically Formed Nanowires	166
7.4	Quantization of Thermal Conductance in Nanostructures	167
7.5	Scientific and Technological Impacts of Conductance Quantization in Nanostructures	169
	References.	171
8	Single Electron Tunneling	173
8.1	Electron Tunneling	173
8.1.1	Phenomenon of Tunneling	173
8.1.2	Theory of Single Electron Tunneling	174
8.2	Electronic Circuits with SET Junctions	176
8.2.1	SETT Transistor	176
8.2.2	Electron Pump and Turnstile Device	178
8.3	Capacitance Standard Based on Counting Electrons	180
8.4	Thermometer with the Coulomb Blockade	182
	References.	184
9	Atomic Clocks and Time Scales	187
9.1	Theoretical Principles	187
9.1.1	Introduction	187
9.1.2	Allan Variance	190
9.1.3	Structure and Types of Atomic Standards	193
9.2	Caesium Atomic Frequency Standards	195
9.2.1	Caesium-Beam Frequency Standard	195
9.2.2	Caesium Fountain Frequency Standard	198

9.3	Hydrogen Maser and Rubidium Frequency Standard	200
9.3.1	Hydrogen Maser Frequency Standard	200
9.3.2	Rubidium Frequency Standard	202
9.3.3	Parameters of Atomic Frequency Standards	203
9.4	Optical Radiation Frequency Standards	204
9.4.1	Sources of Optical Radiation	204
9.4.2	Optical Frequency Comb	206
9.5	Time Scales	209
9.6	National Time and Frequency Standard in Poland	212
	References.	214
10	Standards and Measurements of Length	215
10.1	Introduction	215
10.2	Realization of the Definition of the Metre	217
10.2.1	CIPM Recommendations Concerning the Realization of the Metre.	217
10.2.2	Measurements of Length by the CIPM Recommendation	221
10.3	Iodine-Stabilized 633 nm He-Ne Laser	223
10.4	Satellite Positioning Systems	226
10.4.1	Positioning Systems	226
10.4.2	Global Positioning System	227
10.4.3	GLONASS Positioning System.	231
10.4.4	Galileo Positioning System	234
10.4.5	Regional Positioning Systems: BeiDou, IRNSS and QZSS.	234
	References.	235
11	Scanning Probe Microscopes	237
11.1	Atomic Resolution Microscopes	237
11.1.1	Operating Principle of a Scanning Probe Microscope	237
11.1.2	Types of Near-Field Interactions in SPM.	238
11.1.3	Basic Parameters of SPM.	239
11.2	Scanning Tunneling Microscope	240
11.3	Atomic Force Microscope	243
11.3.1	Atomic Forces	243
11.3.2	Performance of Atomic Force Microscope	244
11.3.3	Measurements of Microscope Cantilever Deflection.	245
11.3.4	AFM with Measurement of Cantilever Resonance Oscillation	248

11.4	Electrostatic Force Microscope	249
11.5	Scanning Thermal Microscope	250
11.6	Scanning Near-Field Optical Microscope	253
11.7	Opportunities of Scanning Probe Microscopy Development . . .	255
	References.	255
12	New Standards of Mass	257
12.1	Introduction	257
12.2	Mass Standards Based on the Planck Constant	260
	12.2.1 Watt Balance Standard	260
	12.2.2 Levitation Standard and Electrostatic Standard	264
12.3	Silicon Sphere Standard.	265
	12.3.1 Reference Mass and the Avogadro Constant.	265
	12.3.2 Measurement of Volume of Silicon Unit Cell.	267
	12.3.3 Measurement of Volume of Silicon Sphere	268
12.4	Ions Accumulation Standard.	270
	References.	272
	Index	273